EFFECT OF VARYING DIMENSION ON CRITICAL CURRENTS IN THIN INDIUM FILMS

JAMES F. WRIGHT
AND
CHARLES S. BIRD

EFFECT OF VARYING DIMENSION ON
CRITICAL CURRENTS IN THIN INDIUM FILMS

* * * * * *

James F. Wright, Jr.
Charles S. Bird

EFFECT OF VARYING DIMENSION ON CRITICAL CURRENTS IN THIN INDIUM FILMS

by

James F. Wright, Jr.

Lieutenant Colonel, United States Army

and

Charles S. Bird

Submitted in partial fulfillment of
the requirements for the degree of

BACHELOR OF SCIENCE

IN

PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 5 8

EFFECT OF VARYING DIMENSION ON CRITICAL CURRENTS IN THIN INDIUM FILMS

by

Charles S. Bird

Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE

IN

PHYSICS

United States Naval Postgraduate School
Monterey, California

1 9 5 8

EFFECT OF VARYING DIMENSION ON

CRITICAL CURRENTS IN THIN INDIUM FILMS

by

James F. Wright, Jr.

This work is accepted as fulfilling

the thesis requirements for the degree of

BACHELOR OF SCIENCE

IN

PHYSICS

from the

United States Naval Postgraduate School

ABSTRACT

This paper reports the results of measurements of the effect of film width and film thickness on critical current for cessation of superconductivity in superconducting thin films. Indium specimens ranging in width from 0.0127 centimeter to 0.0508 centimeter and in thickness from 1.11×10^{-5} centimeter to 4.44×10^{-5} centimeter were examined in the temperature range from 2.7° K to 3.4° K. In this temperature range it was found that critical current is approximately proportional to film width and essentially independent of film thickness.

ACKNOWLEDGMENTS

The writers wish to express their appreciation for the advice, assistance, and encouragement given them by Professor Eugene C. Crittenden, Jr., Professor John N. Cooper, and Mr. Kenneth C. Smith of the United States Naval Postgraduate School.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

1. Introduction.

Various aspects of superconductivity have attracted a great deal of study since the discovery of the phenomena by Kamerlingh Onnes in 1911. The first characteristic property of superconductors, that of the disappearance of electrical resistance below a certain temperature, was discovered at that time. The temperature at which the resistance disappears is called the transition temperature.

When an external magnetic field of sufficient intensity is applied to a superconductor, a transition from the superconducting state to the normal or resistive state occurs. The magnetic field required to cause this transition to take place is called the threshold field. Curves showing the relationship of threshold field with temperature for various metals are shown in Figure 1.[1]

When a steadily increasing current is passed through a superconductor, the field associated with the current eventually becomes great enough to destroy the superconductivity. The maximum current which the superconductor can carry without becoming resistive is called the critical current. A relationship between critical current and threshold field in wires was suggested by Silsbee.[2] In thin films, however, the current is

[1] D. Shoenberg, Superconductivity, pp. 224-225; Cambridge, University Press, 1952.

[2] S. Flügge (Ed.), Handbuch der Physik, Volume XV, pp. 253-254; Berlin, Springer-Verlag, 1956.

probably concentrated near the edges and the current distribution function has not yet been determined. No definite relationship between critical current and threshold field has been established for thin films.

In this experiment it was decided to make specimens with indium films of various widths and thicknesses, and to measure the critical current variation with temperature. With this data it was expected that some idea of the effects of width and thickness on critical current could be determined.

It is hoped that this work will help lay the foundation for a continuing study of the current and field relationships in superconducting thin films.

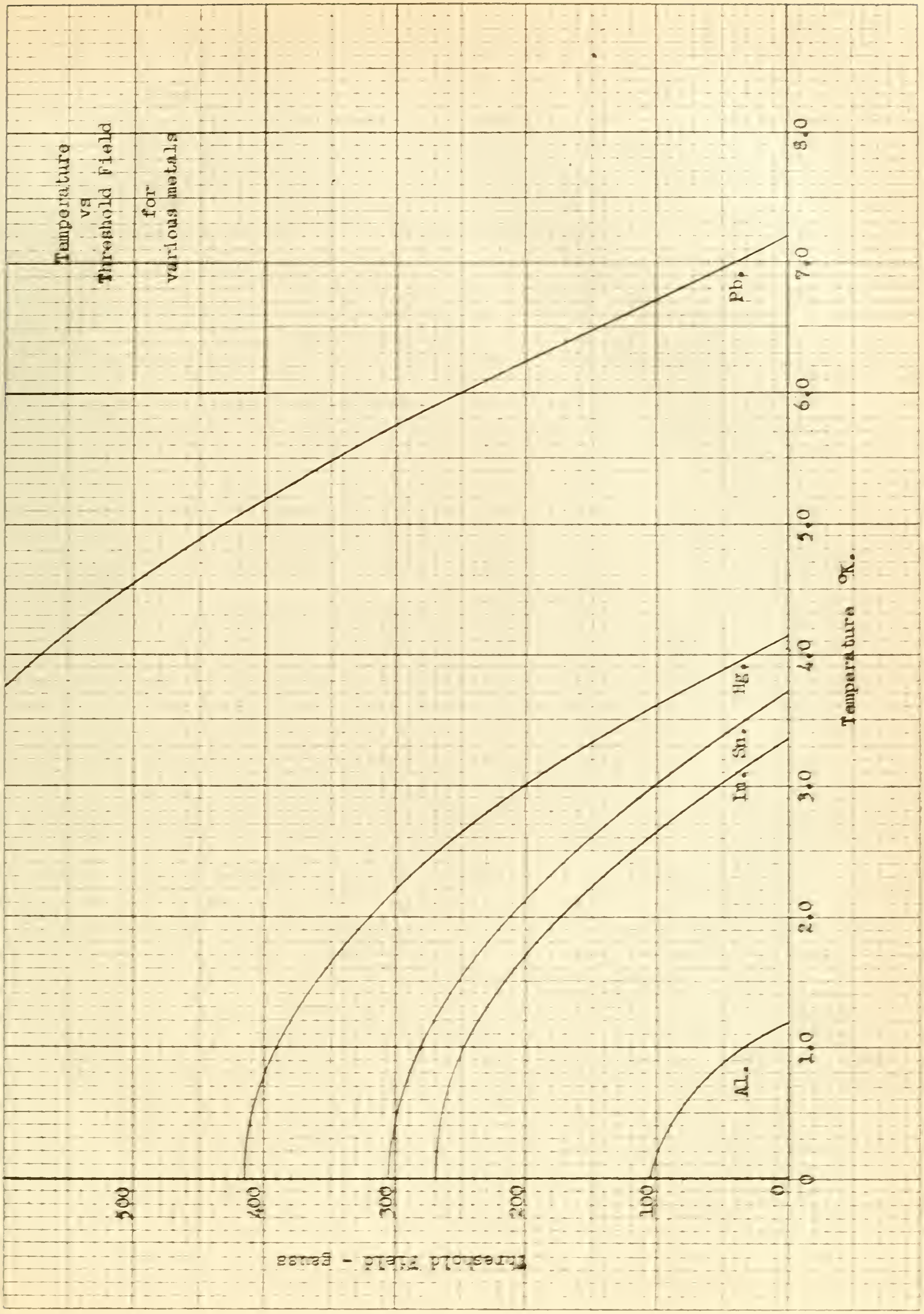

Temperature
vs
Threshold Field
for
various metals
Threshold Field - gauss
Temperature °K.
Pb.
Hg.
Sn.
In.
Al.
0
100
200
300
400
500
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0

Figure 1

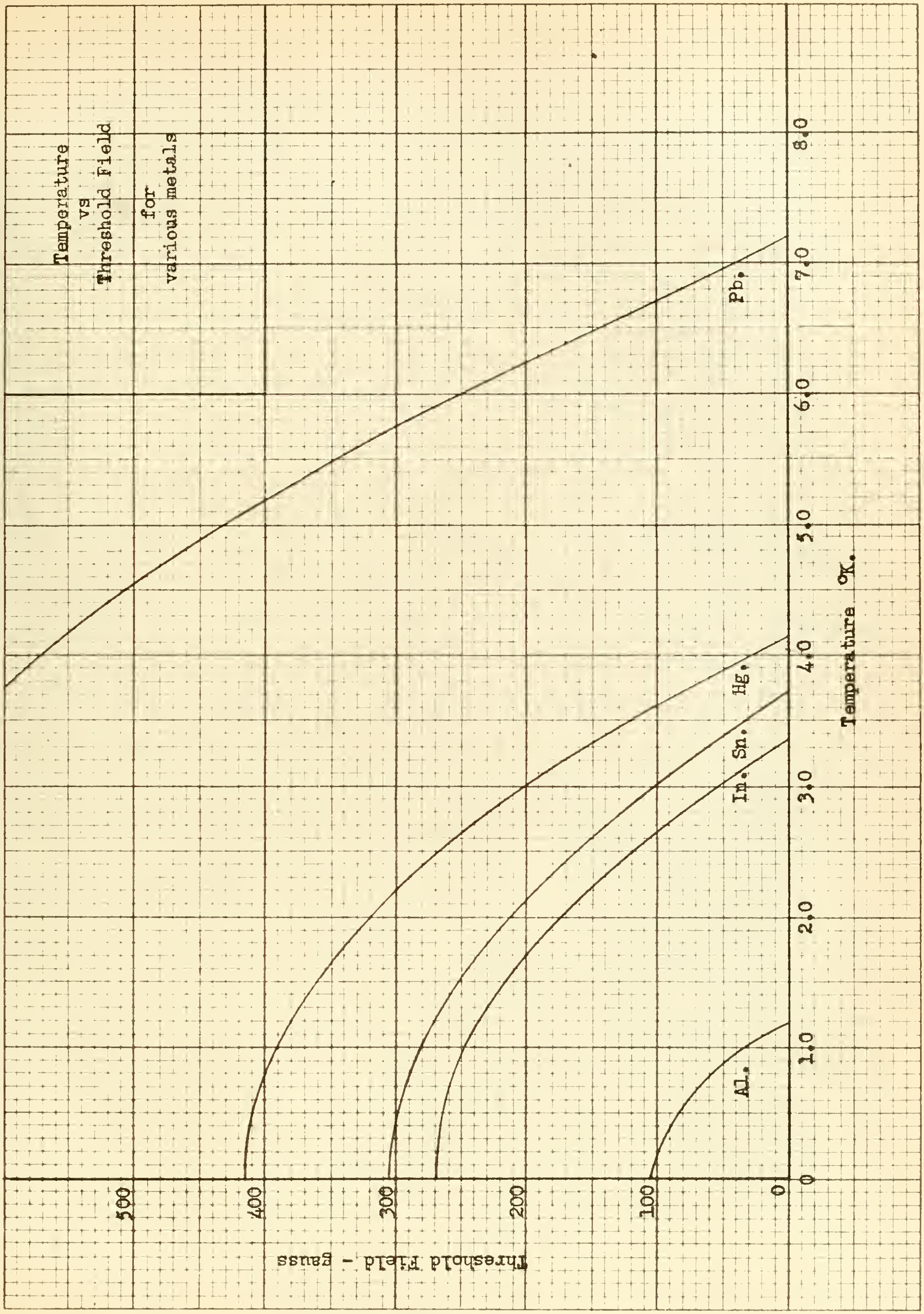

Temperature
vs
Threshold Field
for
various metals
Threshold Field - gauss
Temperature °K.
0
100
200
300
400
500
0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
Al.
In.
Sn.
Hg.
Pb.

Figure 1

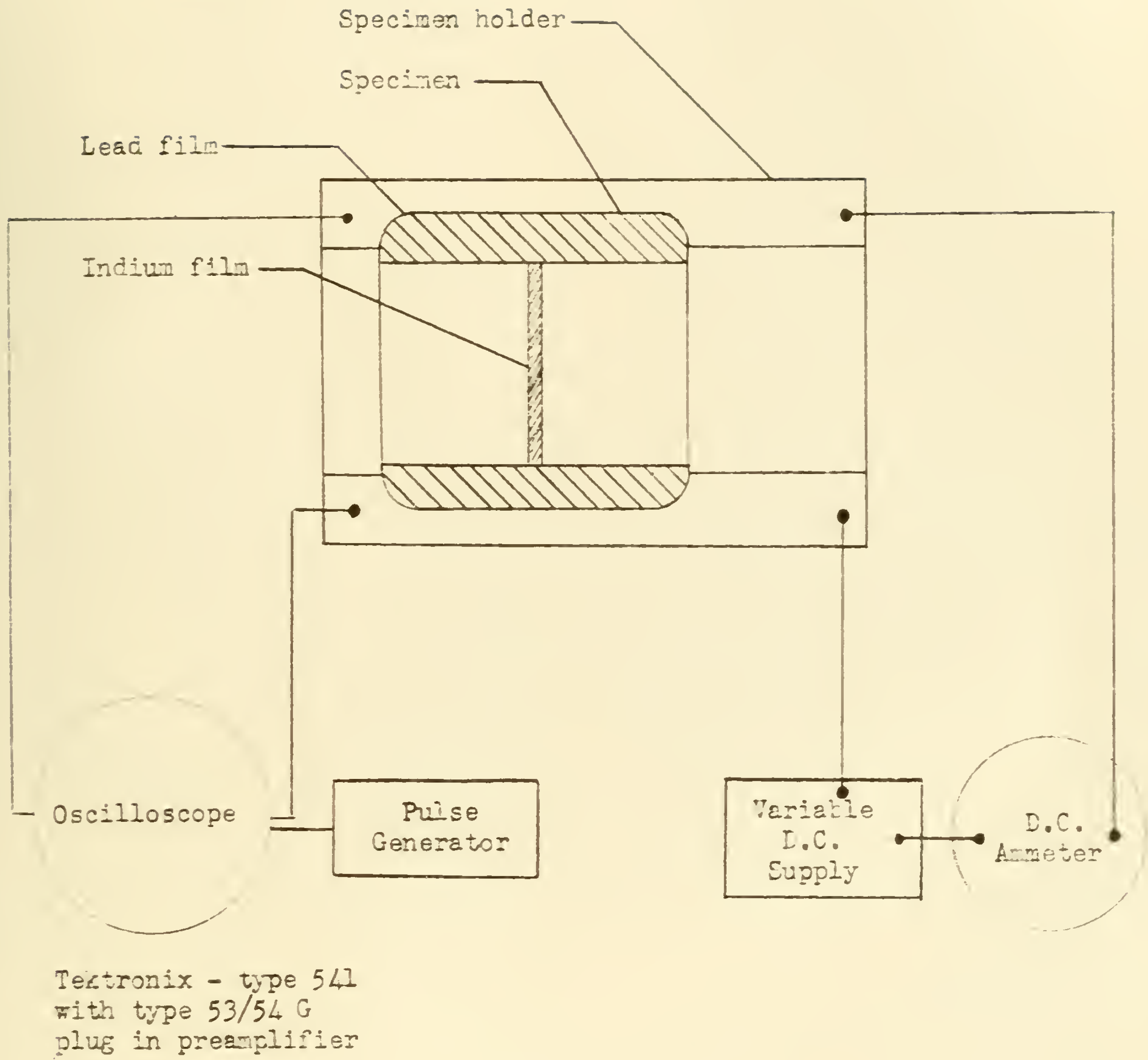
2. Specimen preparation.

The specimens were prepared by using the evaporated metallic film technique to deposit on laboratory grade microscope glass slides (14 x 25 millimeters) two lead (Pb) conduction borders approximately five millimeters wide with a 6.34 millimeter separation between them. This separation determined the length of the indium test film and was kept constant for all specimens. An indium film of the desired width and thickness was then evaporated between the lead (Pb) borders and covered by evaporating a coating of silicon monoxide over the indium. Figure 2 shows a diagram of the specimen. The silicon monoxide was used as it was felt that an inert nonconducting coating would reduce any tendency of the indium test film to oxidize and thereby reduce a possible variation in the superconductivity characteristics of the specimen.

The glass slides were cut to size, cleaned with alcohol, and dried. The lead (Pb) conduction borders were evaporated to a thickness of 5×10^{-4} centimeter at a pressure of 5×10^{-5} millimeters of mercury. The indium films were evaporated to the desired widths and thicknesses at pressures of 5 to 8×10^{-6} millimeters of mercury and the silicon monoxide coatings were evaporated to the desired thickness at pressures of 3 to 9×10^{-6} millimeters of mercury.

The desired thicknesses of the films were obtained by calculating the required length of indium wire of known mass

per unit length for each thickness utilizing Lambert's Law for the distribution of flux. The calculations involved in determining the length of indium wire to be used and the range of specimen sizes utilized are given in detail in Appendix I.



ELECTRICAL SCHEMATIC

Figure 2

3. Experimental procedures.

The superconductivity characteristics of the test specimens were investigated by determining the direct current required to cause a voltage drop across the specimen at a particular temperature. This voltage drop indicated the change from the superconducting state to the resistive state.

The specimens were mounted in a plastic holder which was fitted with lead (Pb) foil strips to insure electrical contact between the external measuring instruments and the lead (Pb) borders of the specimens. A variable direct current supply was used to apply the current to the specimens and an oscilloscope provided a visual presentation of the voltage drop across the specimens when the phase change occured. A schematic wiring diagram is shown in Figure 2 and a block diagram of the equipment used in this work is shown in Figure 3.

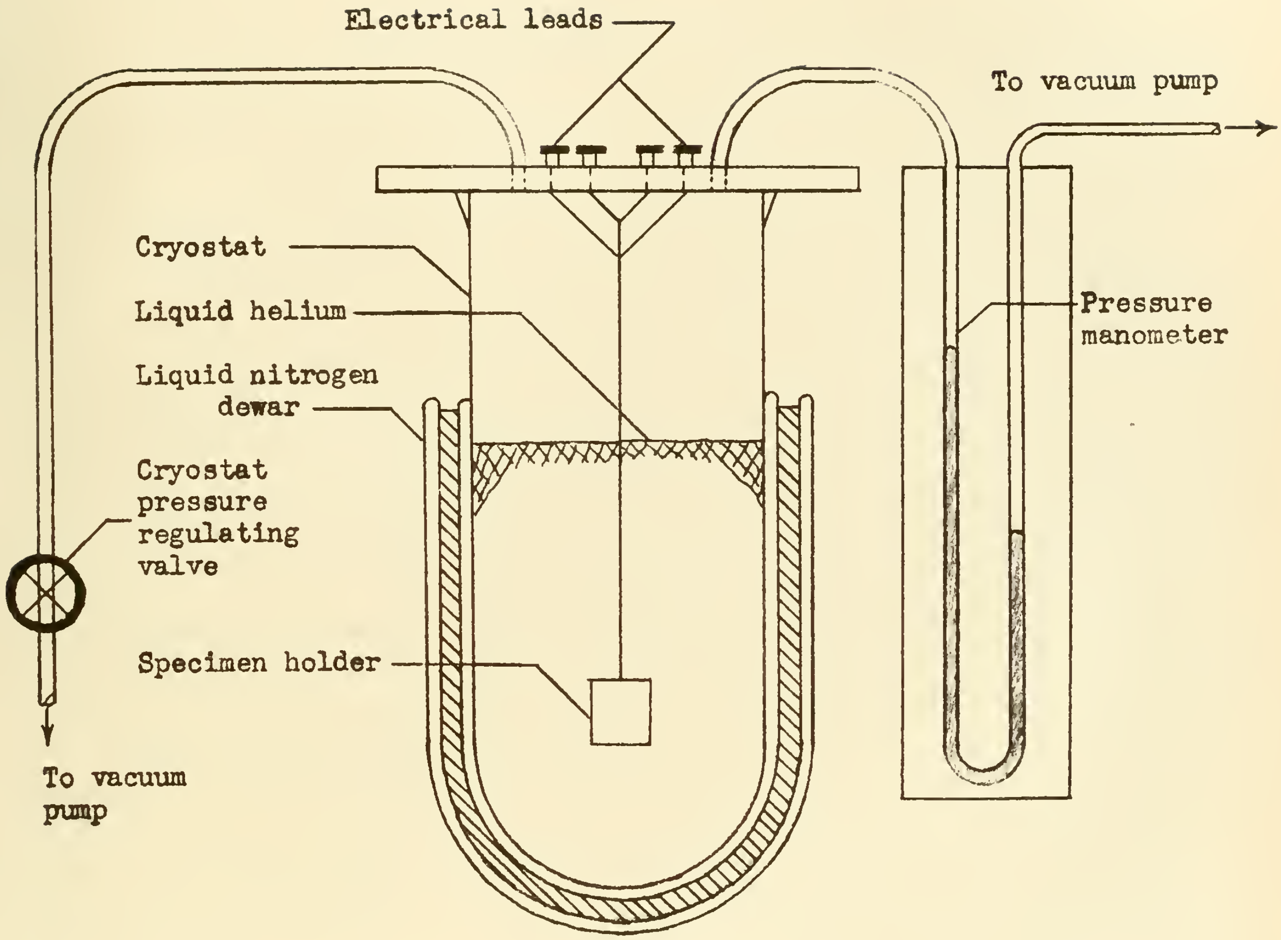
The cryostat, specimen, and specimen holder were precooled with liquid air prior to filling the cryostat with liquid helium. The loaded cryostat was allowed to reach temperature equilibrium, as indicated by the cessation of boiling, and the resistance of the specimen at atmospheric pressure (4.2°K) was determined.

The pressure was then reduced to 325 millimeters of mercury (3.432°K) and allowed to stabilize. The pressure was then decreased in five millimeter increments until the specimen became superconducting.

After the specimen became superconducting a direct current was applied to the specimen and the current required to cause the phase change to the resistive state was measured by observing the current value when the oscilloscope trace indicated a change in the voltage across the specimen. This procedure was repeated at pressure intervals of five to fifteen millimeters (0.013 to 0.040°K).

The readings reported were the average of three current determinations at each value of temperature. The pressure was always decreased between readings in order to assist in reaching and maintaining temperature equilibrium, and in no case was the specimen allowed to warm up during a run.

Values of current are considered accurate within one milliampere in the range from 0 to 100 milliamperes; within two milliamperes in the range from 100 to 150 milliamperes; and within three milliamperes in the range from 150 to 200 milliamperes. Pressure readings are considered accurate within one millimeter of mercury, corresponding to temperature values of $\angle$ 0.003° for the range from 3.5 to 3.2°K; $\angle$ 0.004° for the range from 3.2 to 2.9°K; $\angle$ 0.005° for the range from 2.9 to 2.6°K; and $\angle$ 0.006° for the range from 2.6 to 2.3°K. These estimates are based on instrument scale divisions and the difficulty of reading constantly changing instrument indications.



EQUIPMENT SCHEMATIC

Figure 3

4. Experimental results.

The values of temperature and critical current obtained for each specimen tested are tabulated in Appendix II. The curves of Figures 4 through 7 are a graphical representation of this data shown by families of specimens having the same width.

In those cases where later runs were made using the same specimens, agreement of data was considered very satisfactory. This is felt to be due in large part to the protection against oxidation furnished by the coating of silicon monoxide.

Anomalous results were noted on two specimens- 2C3D and 5D3G. On these two specimens the critical current vs. temperature curves became horizontal at a relatively high temperature. Successive jumps of voltage across the specimen were observed at three, four, or five values of current at the same temperature. This action is attributed to extreme irregularities on the surface of the film noted in subsequent microscopic examination.

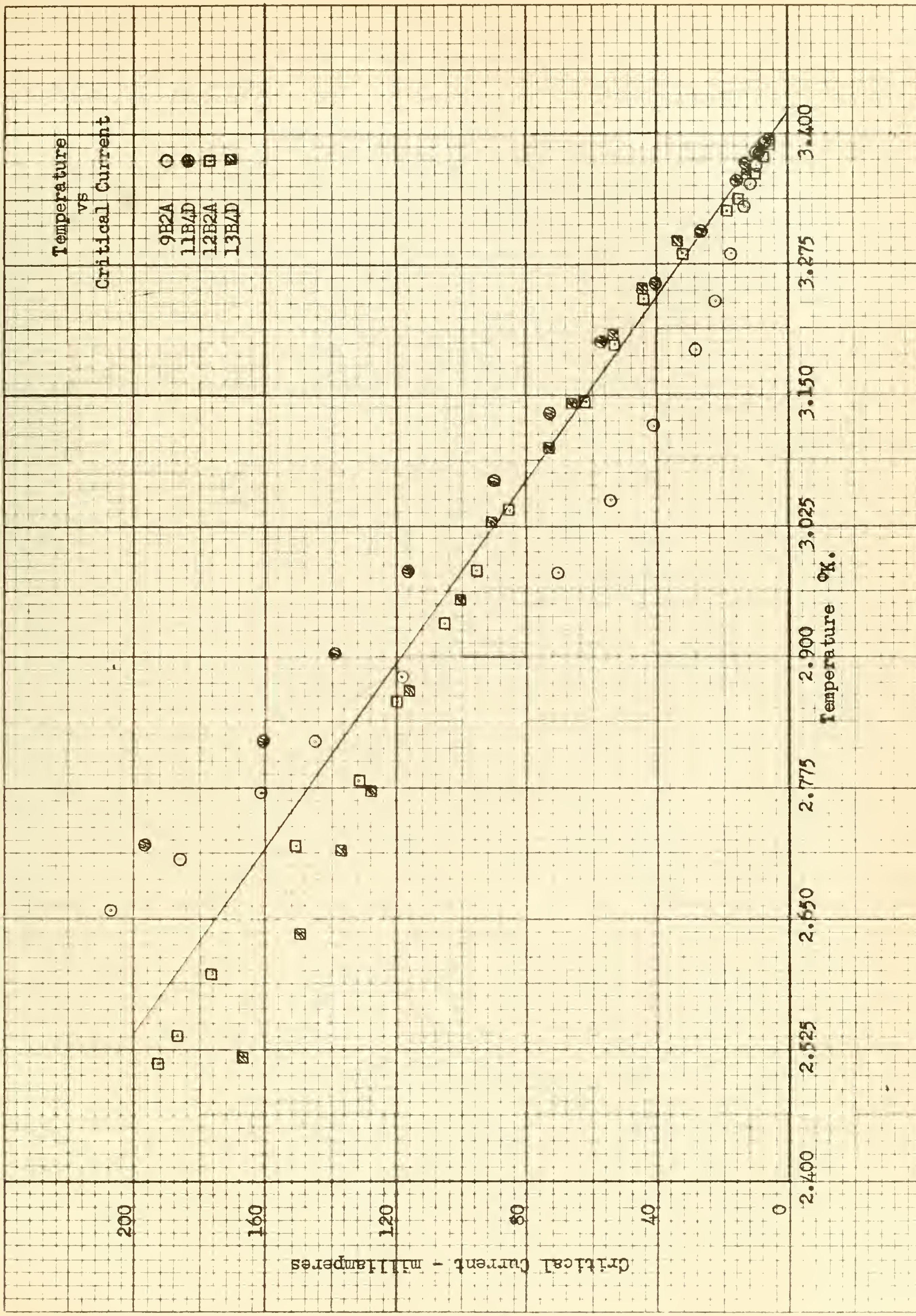

Temperature
vs
Critical Current
9B2A
11B4D
12B2A
13B4D
Critical Current - milliamperes
200
160
120
80
40
0
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
Temperature °K.

Figure 4

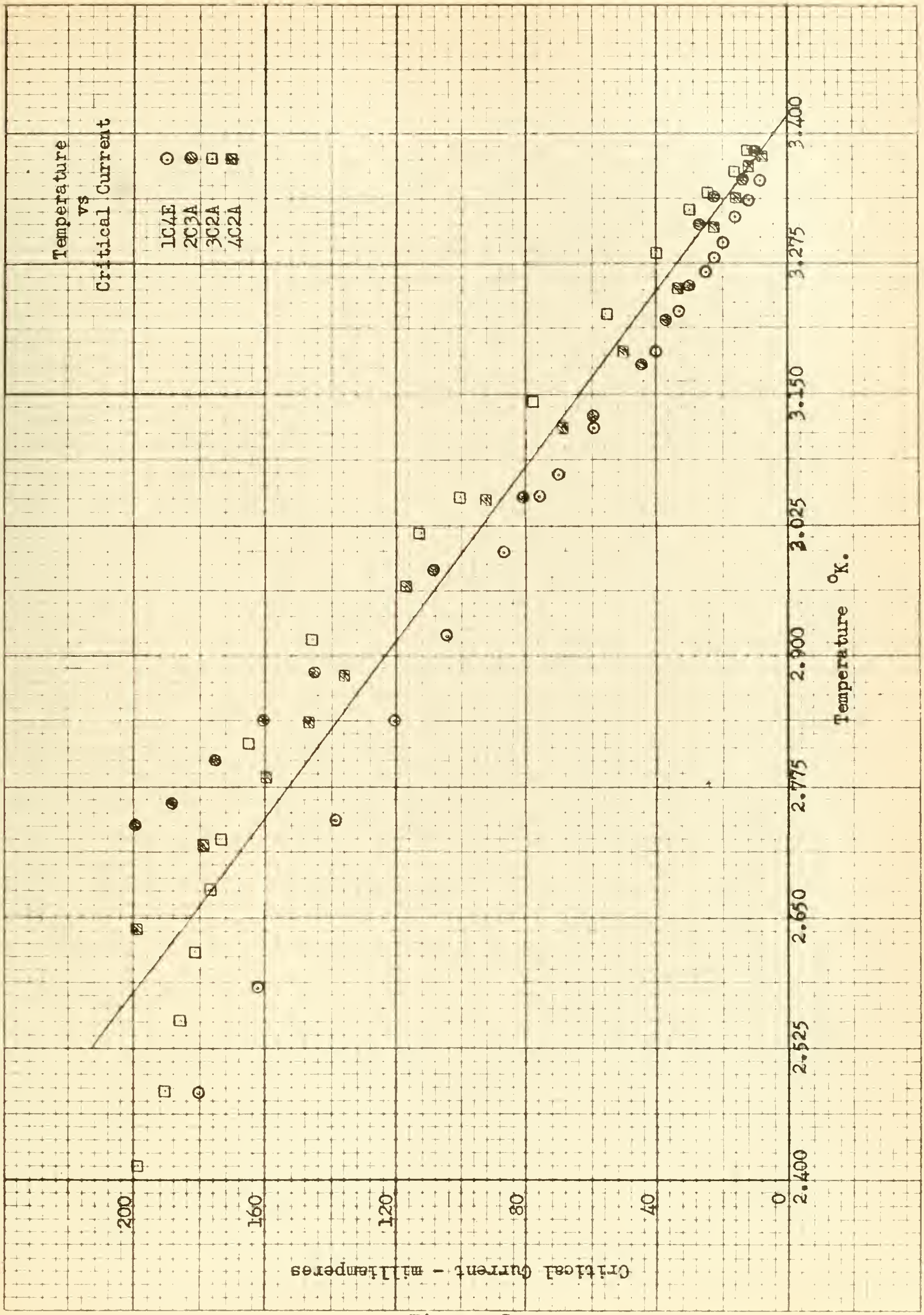

Temperature
vs
Critical Current
1C4E
2C3A
3C2A
4C2A
Critical Current - milliamperes
200
160
120
80
40
0
Temperature °K.
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400

Figure 5

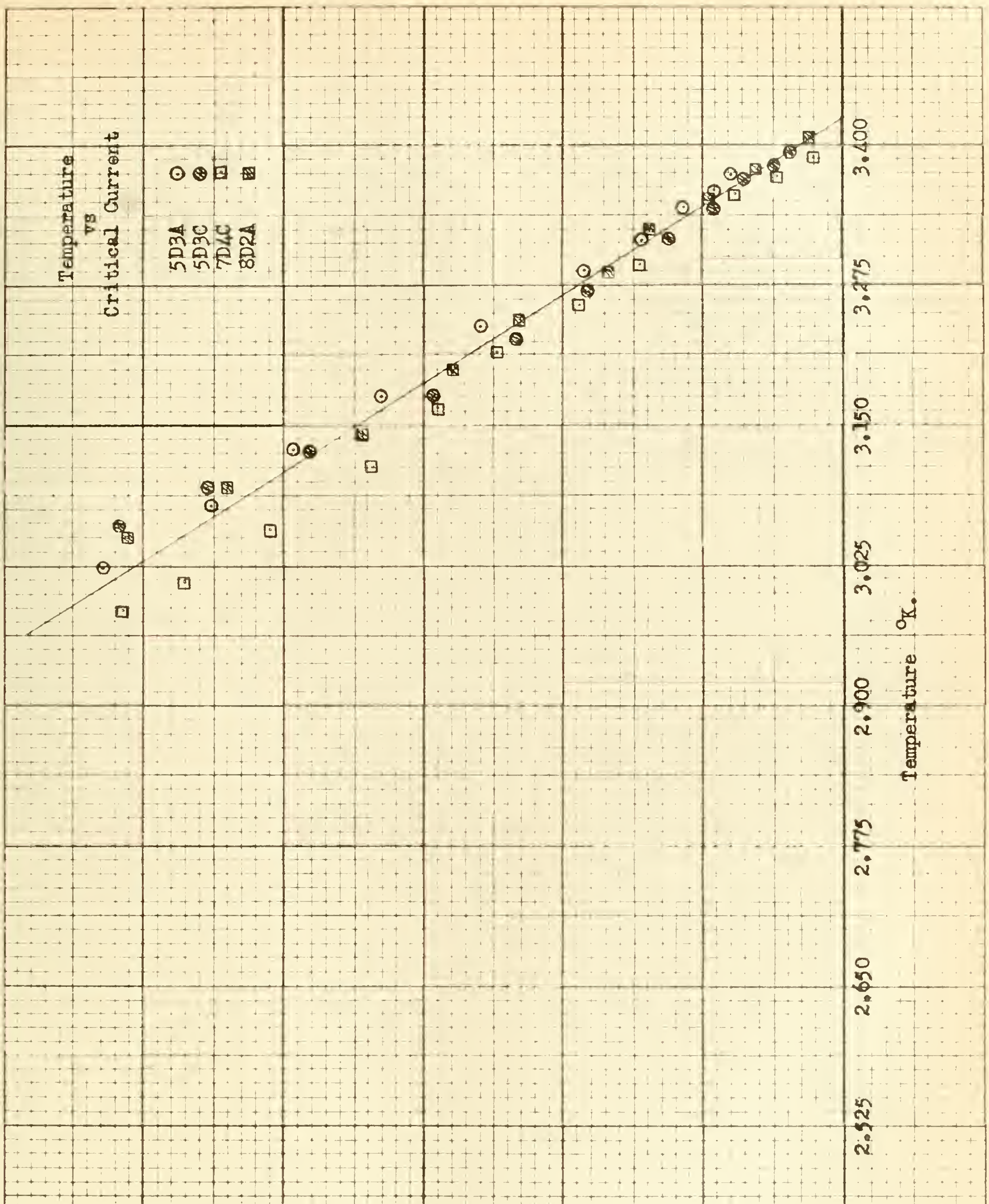

Temperature
vs
Critical Current
5D3A
5D3C
7D4C
8D2A
Critical Current - milliamperes
0
40
80
120
160
200
Temperature °K.
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400

Figure 6

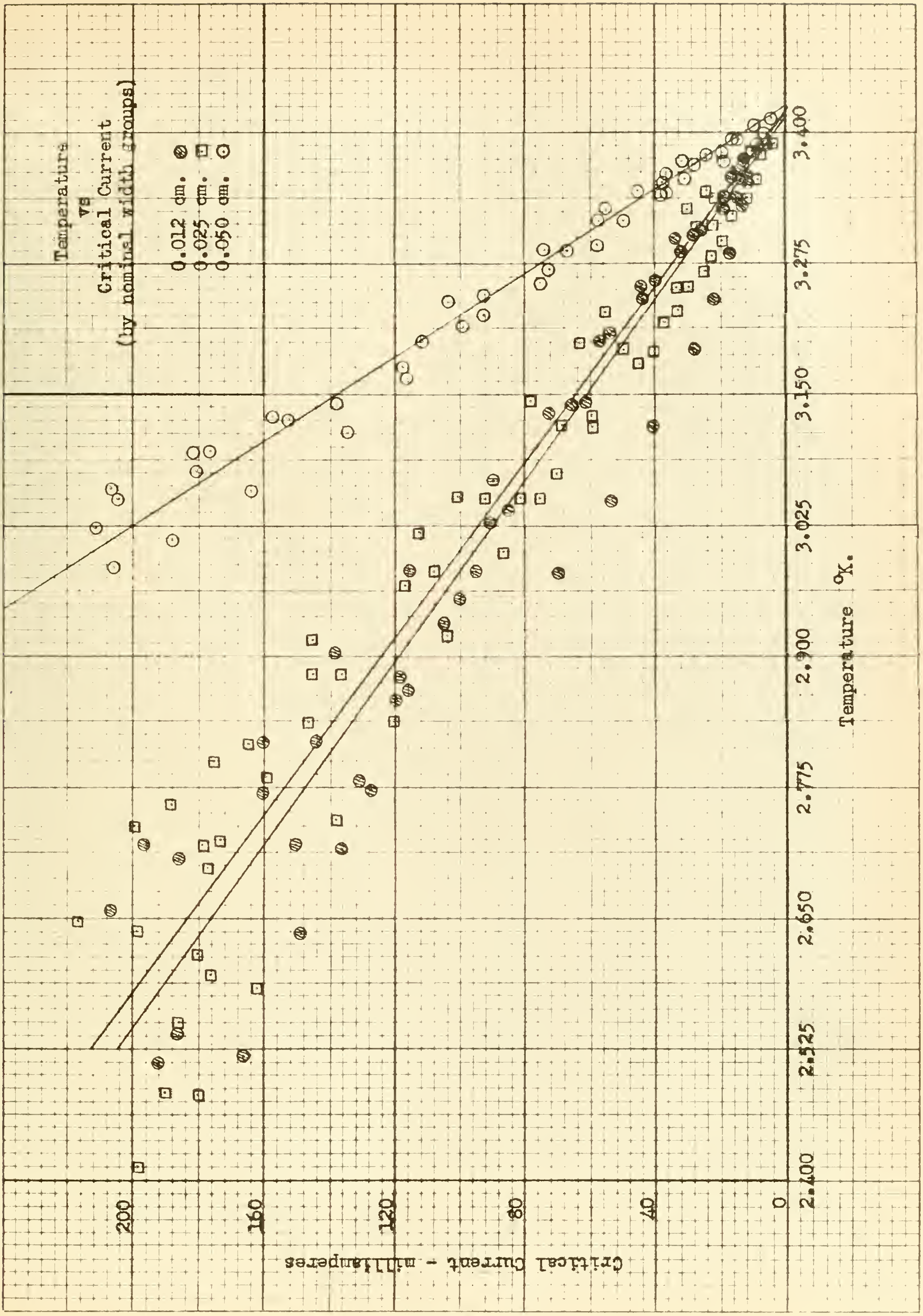

Temperature
vs
Critical Current
(by nominal width groups)
0.012 cm.
0.025 cm.
0.050 cm.
Temperature °K.
Critical Current - milliamperes
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
0
40
80
120
160
200

Figure 7

5. Conclusions.

An examination of the data accumulated, and of Figures 4 through 7 indicates that varying the width of the film has a definite effect on the critical current. No effect was noted as a result of varying the thickness.

The Meissner effect[3] shows that the magnetic induction inside a superconductor is zero. Actually there is a slight penetration of the magnetic field into the superconductor, on the order of 10^{-6} centimeter, known as the penetration depth.[4] This indicates that superconductivity is essentially a surface effect. In studying thin films we would expect only a slight variation of critical current with the thickness of the film for films appreciably thicker than the penetration depth. Although the current distribution in the film has not been determined, the current is considered to be concentrated toward the edges of the film due to the inability of the magnetic field to penetrate the superconductor.[5] It would therefore be expected that the variation of critical current with width would be non-linear in nature. The curves plotted from the date obtained in these experiments, however, indicate that this relationship might in fact be linear. In order to study this more carefully the data was replotted in the form of critical current divided by width vs. temperature.

[3]Flugge, op.cit., pp. 211-212.

[4]ibid., p. 241ff.

[5]Shoenberg, op.cit., p.177.

These curves are shown as Figures 8 through 11.

Study of these curves seems to show that there might be some variation of critical current/width vs. temperature with specimen width, which would indicate a non-linearity of the critical current-width relationship. Considerable overlap exists in these curves, however, which may account for this apparent variation with width. This overlap is caused partially by the experimental errors in measuring critical current and temperature and partially by the indeterminate nature of the measure of specimen width. Nicks, scratches, and surface irregularities may give the specimen an effective width differing from the measured value. Even in the case of measurable abnormalities, such as nicks in the sides of the film, it generally cannot be determined whether the damage occured before readings were made, during the taking of measurements, or after readings had been completed. The magnitude of the effect of these irregularities could not be definitely ascertained. In the case of specimens 2C3D and 5D3G, previously mentioned, the surface irregularities were quite pronounced, and the behavior of the specimens was anomalous. Specimens with defects which were not apparent on close examination may nevertheless have been affected to some extent.

Taking these two sources of scattering into account, it would appear from this data that the relationship between critical current and specimen width is effectively linear to temperatures as low as $2.7^{\circ}K$.

Another phenomena observed was the linear relationship between critical current and temperature to temperatures as low as 2.7°K. The behavior of this curve at lower temperatures is still uncertain; and although thermodynamic considerations make it clear that the current must be independent of temperature near 0°K, the magnitude of the critical current at that point is not known.

The average transition temperature observed during the conduct of the experiment was 3.425°K, slightly higher than the generally accepted value for bulk specimens of 3.396°K. This increase is probably due to the tension induced in the film on being cooled to liquid helium temperatures as a result of the different coefficients of thermal expansion of the indium film and glass backing material.

Certain conclusions can also be drawn as to the practicability of certain film dimensions. With the techniques used in this experiment films of a thickness of about 1×10^{-5} centimeter appeared to be the thinnest that could be produced. Films of this thickness were produced at the center position of the vapor plating holder using two centimeters of indium wire, as described in Appendix IB. The outer positions produced specimens with a thickness calculated as 0.68×10^{-5} centimeter, and although several of these specimens appeared to provide the necessary conduction paths, all had infinite resistance. It is believed that by cooling the specimens while they are being vapor plated a film with a smoother surface will result and films thinner than those produced without cooling will be possible.

It was also noted that films of the greatest width did not have as sharp a transition from the superconducting to the resistive phase as did the films of standard and half standard width. It is possible that the wider films show wider variations due to surface irregularities than the narrower films. In this case also, cooling the specimens during the vapor plating operation should improve the performance of the specimens.

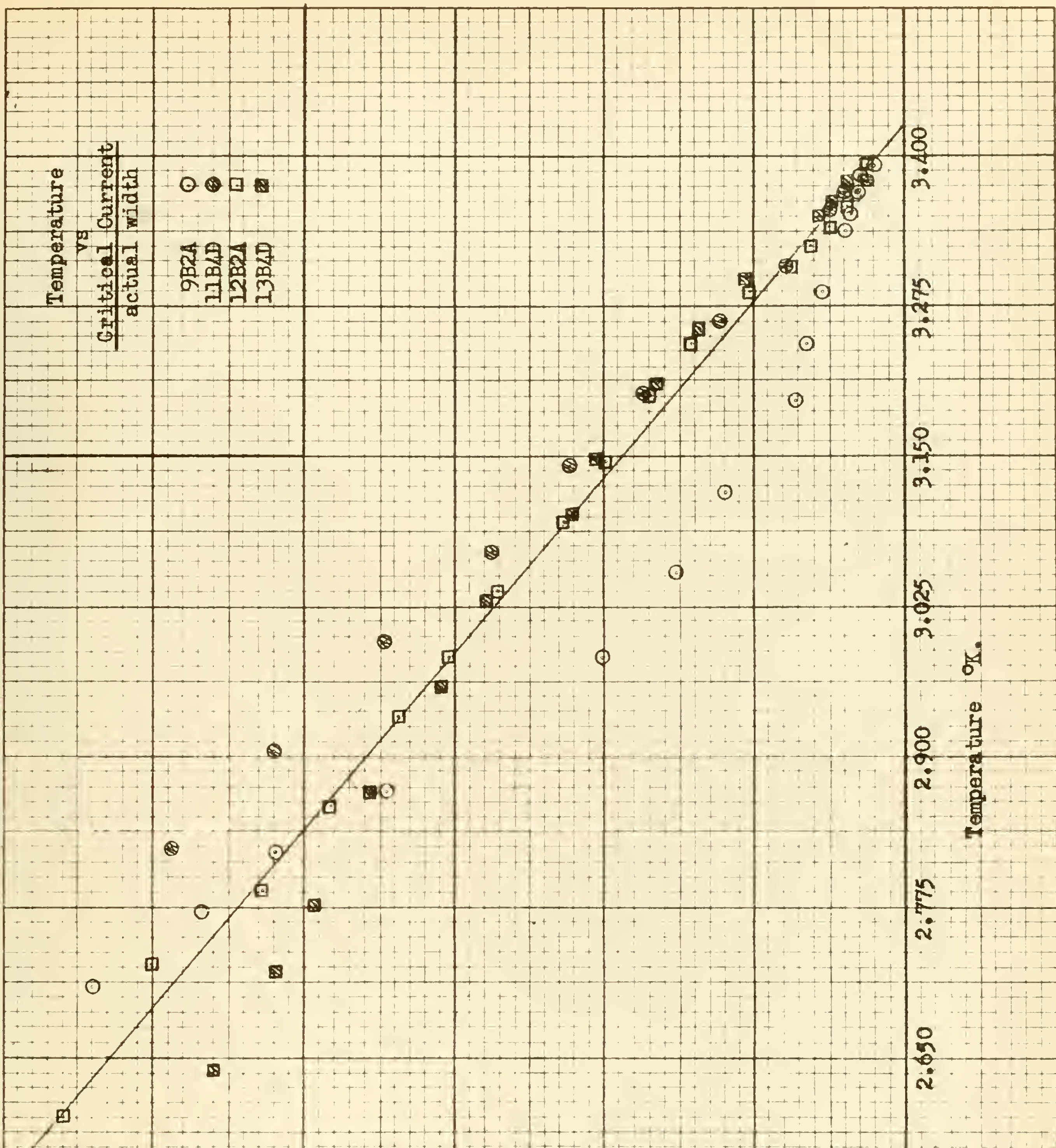

Temperature
vs
Critical Current
actual width
9B2A
11B4D
12B2A
13B4D
Critical Current
actual width
ampere
centimeters
Temperature °K.
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
0
2
4
6
8
10

Figure 8

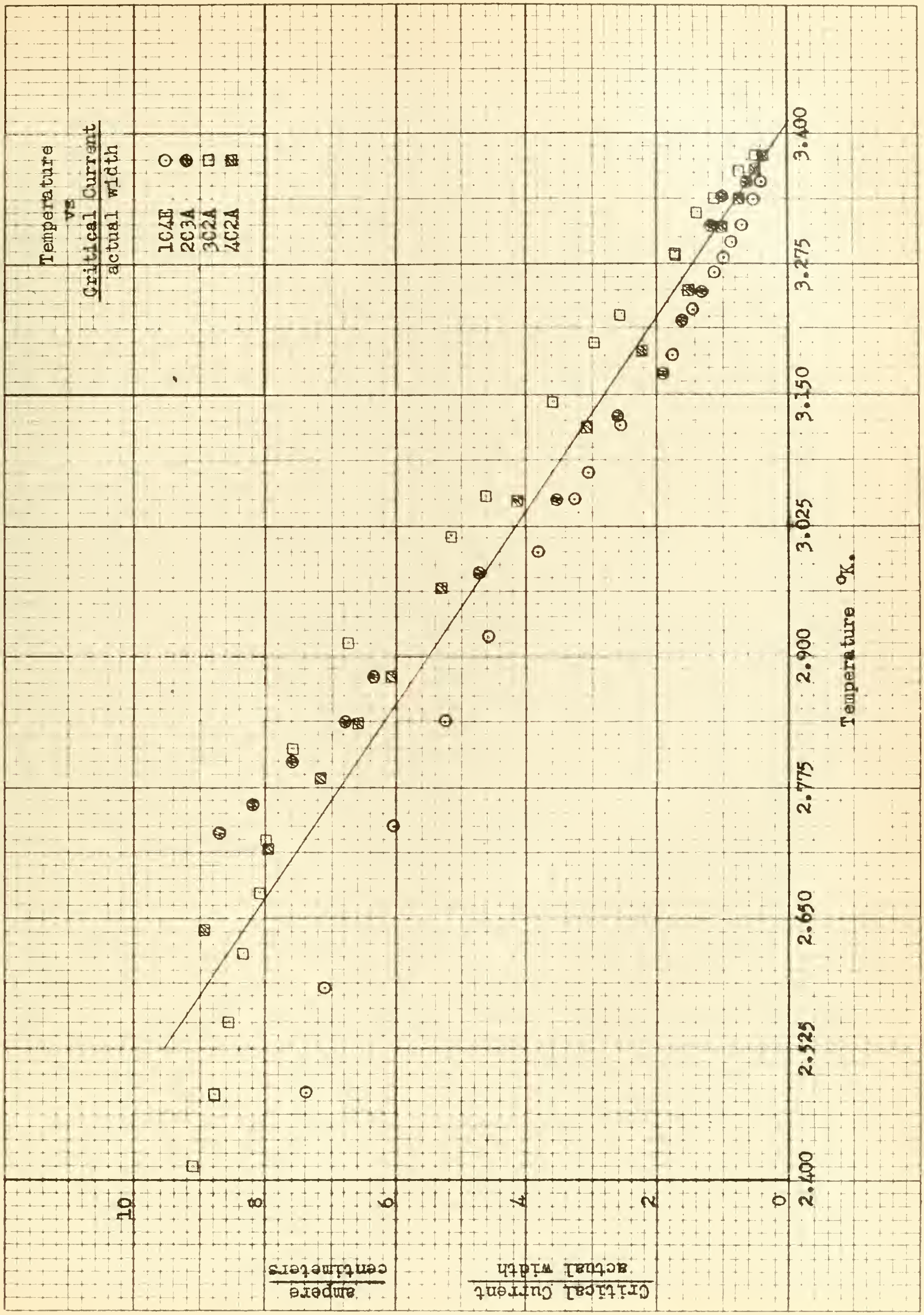

Temperature
vs
Critical Current / actual width
1C4B
2C3A
3C2A
4C2A
Critical Current / actual width
ampere / centimeters
0
2
4
6
8
10
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
Temperature °K.

Figure 9

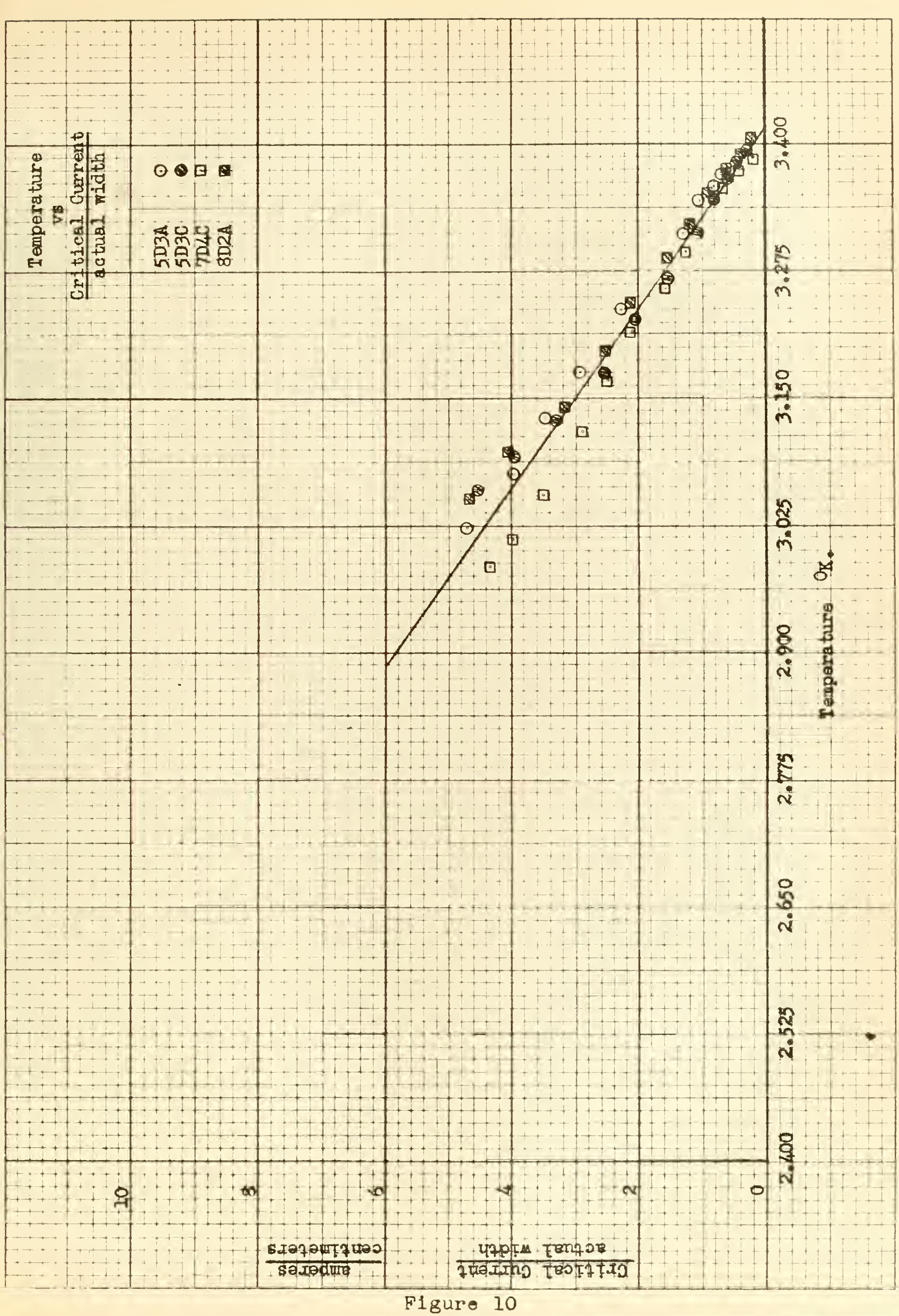
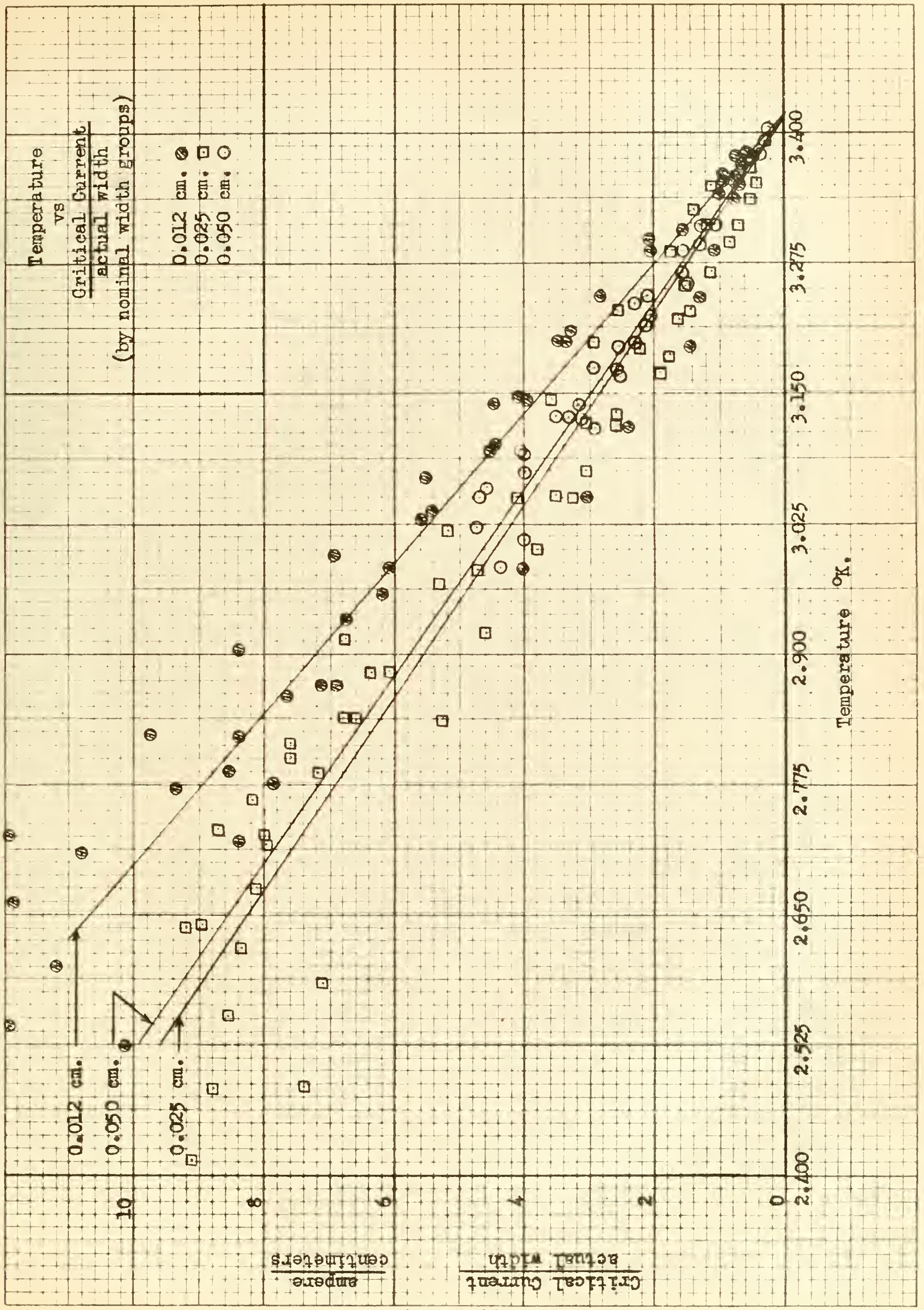

Temperature
vs
Critical Current / actual width
5D3A
5D3C
7D4C
8D2A
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
Temperature °K.
0
2
4
6
8
10
Critical Current / actual width
amperes / centimeters

Figure 10



Temperature
vs
Critical Current
actual width
(by nominal width groups)
0.012 cm.
0.025 cm.
0.050 cm.
0.012 cm.
0.050 cm.
0.025 cm.
2.400
2.525
2.650
2.775
2.900
3.025
3.150
3.275
3.400
Temperature °K.
0
2
4
6
8
10
Critical Current
actual width
ampere
centimeters

Figure 11

6. Fields for future study.

Several fields for future study are suggested by the results of this experiment. A few of them are briefly discussed here.

A. Comparison of critical current and threshold field data.

It would be interesting to compare the critical current vs. temperature curves with threshold field vs. temperature curves obtained by applying an external magnetic field to the specimens used in this experiment, or to similar specimens.

B. Examination of films of other dimensions.

By repeating this experiment with specimens in a wider range of widths the suspected linearity of the critical current- width relationship could be confirmed or disproved.

C. Effects of applied pulses.

A study of the transitions brought about by applied pulses of various sizes and shapes instead of a direct current might prove of great interest in the study of the field of superconducting transitions.

The field of superconducting transitions in general, and especially that of transitions in superconducting thin films, is one offering many openings for work which will increase our knowledge and understanding of this phenomena.

BIBLIOGRAPHY

1. E. F. Burton, H. Grayson Smith, and J. O. Wilhelm, Phenomena at Temperature of Liquid Helium, Reinhold Publishing Company, 1940.

2. S. Flügge (Ed.), Handbuch der Physik, Volume XV, Springer-Verlag, 1956.

3. C. J. Gorter, Progress in Low Temperature Physics, Interscience Publishers, Inc., 1955.

4. D. Shoenberg, Superconductivity, Cambridge University Press, 1952.

5. C. F. Squire, Low Temperature Physics, McGraw Hill Book Co., Inc., 1953.

6. E. C. Crittenden, Jr., A New Memory Element Employing Persistent Currents in Superconductors, Los Angeles Chapter-Professional Group on Electronic Computers- IRE, June-July 1957.

APPENDIX I

A. Range of specimen sizes used.

In order to fit in with work previously performed in this field by Crittenden and Cooper a "standard" width of 0.0254 centimeter and a "standard" thickness of 2.22×10^{-5} centimeter were chosen for the specimens produced. It was decided to work in addition with specimens of one-half standard and double standard widths and thicknesses.

A coding system for designating the completed specimens was established. Each specimen manufactured was given a designator consisting of a number-letter-number-letter combination. The first number indicated the number of the batch to which the specimen belonged. The first letter indicated the width of the specimen; the second number its thickness. The final letter showed the position of the specimen on the vapor plating holder- position A being the center position and positions B through G being on the outer circle.

The width and thickness designators are given in the following table:

WIDTH DESIGNATOR	WIDTH	THICKNESS DESIGNATOR	THICKNESS
A very narrow	(not used)	1 very thin	(not used)
B half standard	.0127 cm	2 half standard	1.11×10^{-5} cm (A)
C standard	.0254 cm	3 standard	1.35×10^{-5} cm (B-G) 2.22×10^{-5} cm (A)
D double standard	.0508 cm	4 double standard	2.70×10^{-5} cm (B-G) 4.44×10^{-5} cm (A)

Thus specimen 2C3A would be the center specimen of the second batch manufactured, and of standard width and standard thickness.

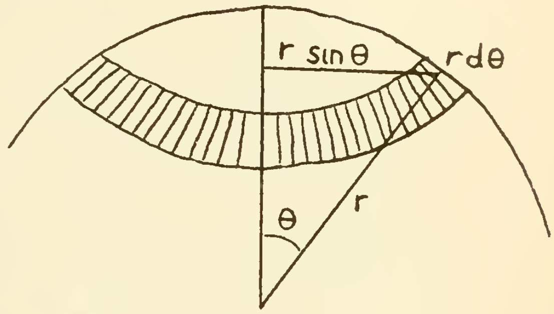
B. Determination of amount of indium required for desired film thicknesses.

The source of indium for the films was indium wire of 0.015 inches diameter with a density of 7.28 grams per cubic centimeter and a length of 120 centimeters per gram.

The determination of the thickness of the films was based on Lambert's Law for distribution of flux:

$$F = F_o \cos \theta$$

$$F_{av} = \frac{\int F dA}{\int dA}$$



Considering the surface area of a hemisphere:

$$dA = 2\pi r \sin \theta \cdot r d\theta = 2\pi r^2 \sin \theta \, d\theta$$

$$F_{av} = \frac{\int_0^{\pi/2} Fo\, 2\pi r^2 \sin \theta \cos \theta \, d\theta}{\int_0^{\pi/2} 2\pi r^2 \sin \theta \, d\theta} = \frac{Fo\ (\frac{1}{2}\sin^2 \theta)_0^{\pi/2}}{(-\cos \theta)_0^{\pi/2}} = \frac{Fo}{2}$$

F_{av} is also equal to $\frac{\text{mass plated}}{\text{area plated}} = \frac{m}{2\pi r^2}$

Since $m = L/120$, $F_{av} = L/240\pi r^2$ and $F_o = 2 F_{av} = L/120\pi r^2$, and in general:

$$F = \frac{F_o \cos \theta}{120\, \pi r^2}$$

The thickness of the film will equal flux/density:

$$t = \frac{L \cos \theta}{120\pi r^2 d}$$

The length of indium wire required to produce a given thickness:

$$L = \frac{120\pi r^2 d}{\cos \theta}\, t$$

With the equipment used for vapor plating in our set-up, the geometry factors were as follows:

For center position (A); $r^2 = 65.61\ cm^2$, $\cos \theta = 1.000$

For outer positions (B-G): $r^2 = 91.39\ cm^2$, $\cos \theta = 0.847$

The necessary lengths of indium wire were determined from this relationship.

The actual lengths of indium wire used and the resulting film thicknesses are given below:

2 cm In	half thickness	1.11×10^{-5} cm (center)
4 cm In	standard thickness	1.35×10^{-5} cm (outer) 2.22×10^{-5} cm (center)
8 cm In	double thickness	2.70×10^{-5} cm (outer) 4.44×10^{-5} cm (center)

APPENDIX II

TABULATED DATA

A. Half width specimens.

Specimen no.:	9B2A	12B2A
Thickness:	1.11×10^{-5} cm	1.11×10^{-5} cm
Width:	0.0173 cm	0.0157 cm
Resistance (300°K):	27.9 ohms	50 ohms
Resistance (4.2°K):	1.25 ohms	2.5 ohms

T (°K)	I_c (ma)	I_c/w (amp/cm)	T (°K)	I_c (ma)	I_c/w (amp/cm)
3.396	7	0.40	3.394	7	0.45
3.384	10	0.58	3.381	8	0.51
3.371	10	0.58	3.368	10	0.64
3.355	12	0.70	3.357	12	0.77
3.331	13	0.75	3.341	15	1.00
3.287	18	1.04	3.328	19	1.21
3.244	22	1.27	3.287	32	2.04
3.195	28	1.62	3.244	44	2.80
3.121	41	2.37	3.198	53	3.38
3.050	54	3.12	3.147	62	3.95
2.981	70	4.05	3.094	71	4.52
2.881	118	6.82	3.039	85	5.40
2.820	144	8.34	2.981	95	6.05
2.770	161	9.32	2.930	105	6.70
2.706	186	10.75	2.859	119	7.60
2.660	206	11.80	2.788	133	8.48
			2.722	150	9.55
			2.599	175	11.15
			2.539	186	11.85
			2.513	192	12.20

Specimen no.:	10B3A	10B3D
Thickness:	2.22×10^{-5}cm	1.35×10^{-5}cm
Width:	0.0188 cm	0.0182 cm
Resistance (300°K):	16.3 ohms	70 ohms
Resistance (4.2°K):	0.33 ohms	3.0 ohms

T (°K)	I_c (ma)	I_c/w (amp/cm)	T (°K)	I_c (ma)	I_c/w (amp/cm)
3.368	14	0.76	3.381	6	0.33
3.349	18	0.96	3.365	10	0.55
3.331	21	1.12	3.347	13	0.72
3.281	28	1.49	3.328	17	0.94
3.241	35	1.86	3.309	20	1.10
3.198	43	2.29	3.258	31	1.70
3.144	55	2.93	3.217	44	2.42
3.094	70	3.71	3.160	70	3.84
3.042	81	4.30	3.114	85	4.66
2.988	96	5.10	3.060	104	5.71
2.906	110	5.85	2.988	132	7.25
2.810	127	6.76			
2.722	145	7.71			
2.587	168	8.94			
2.460	197	10.50			

Specimen no.:	11B4B	11B4D
Thickness:	2.70×10^{-5}cm	2.70×10^{-5}cm
Width:	0.0184 cm	0.0165 cm
Resistance (300°K):	27.5 ohms	23.1 ohms
Resistance (4.2°K):	0.8 ohms	2.5 ohms

T (°K)	I_c (ma)	I_c/w (amp/cm)	T (°K)	I_c (ma)	I_c/w (amp/cm)
3.394	9	0.49	3.381	9	0.55
3.384	10	0.54	3.368	13	0.79
3.371	13	0.70	3.357	16	0.97
3.357	18	0.78	3.309	26	1.57
3.344	21	1.13	3.261	40	2.42
3.301	40	2.15	3.202	57	3.45
3.258	58	3.12	3.134	73	4.42
3.208	74	3.98	3.067	90	5.45
3.164	86	4.62	2.984	115	6.87
3.111	105	5.70	2.902	138	8.36
3.053	130	7.05	2.820	160	9.70
2.996	155	8.42	2.722	196	11.85
2.943	192	10.40			

Specimen no.: 13B4B
Thickness: 2.70×10^{-5} cm
Width: 0.0163 cm
Resistance (300°K): 21.1 ohms
Resistance (4.2°K): 0.65 ohms

T (°K)	I (ma)	I_c/w (amp/cm)
3.391	8	0.49
3.378	12	0.73
3.365	15	0.92
3.352	18	1.10
3.298	34	2.09
3.258	44	2.70
3.208	53	3.25
3.144	66	4.05
3.097	72	4.40
3.028	90	5.52
2.958	100	6.14
2.868	115	7.06
2.774	127	7.80
2.717	136	8.35
2.638	149	9.14
2.520	166	10.10

B. Standard width specimens.

Specimen no.:	3C2A	4C2A
Thickness:	1.11×10^{-5}cm	1.39×10^{-5}cm
Width:	0.0218 cm	0.0224 cm
Resistance (300°K):	36.9 ohms	21.5 ohms
Resistance (4.2°K):	1.8 ohms	0.65 ohms

T ($^{\circ}$K)	I_c (ma)	I_c/w (amp/cm)	T ($^{\circ}$K)	I_c (ma)	I_c/w (amp/cm)
3.384	10	0.46	3.381	8	0.40
3.365	17	0.78	3.368	11	0.49
3.344	24	1.11	3.341	16	0.72
3.328	30	1.39	3.314	22	0.99
3.287	40	1.85	3.255	33	1.47
3.229	55	2.55	3.192	50	2.23
3.198	63	2.92	3.121	69	3.08
3.144	77	3.55	3.050	92	4.10
3.053	100	4.59	2.965	117	5.23
3.018	112	5.15	2.881	135	6.02
2.914	146	6.70	2.833	146	6.52
2.815	165	7.56	2.738	159	7.10
2.722	173	7.94	2.717	178	7.95
2.676	176	8.08	2.638	198	8.84
2.616	181	8.30			
2.551	185	8.49			
2.481	190	8.72			
2.410	198	9.08			

Specimen no.:	2C3A	2C3C
Thickness:	2.22×10^{-5}cm	1.35×10^{-5}cm
Width:	0.0231 cm	0.0276 cm
Resistance (300°K):	12.8 ohms	16.0 ohms
Resistance (4.2°K):	0.5 ohms	0.8 ohms

T (°K)	I (ma)	I_c/w (amp/cm)	T (°K)	I (ma)	I_c/w (amp/cm)
3.357	14	0.60	3.378	15	0.51
3.341	18	0.78	3.363	20	0.73
3.314	23	1.00	3.347	25	0.91
3.281	27	1.17	3.306	38	1.38
3.253	30	1.30	3.261	52	1.87
3.220	37	1.60	3.214	70	2.54
3.180	45	1.95	3.157	96	3.48
3.128	59	2.55	3.094	129	4.68
3.050	81	3.50	3.010	175	6.34
2.981	108	4.68	2.977	195	7.06
2.881	145	6.29			
2.837	160	6.73			
2.801	175	7.57			
2.760	188	8.14			
2.731	199	8.61			

Specimen no.:	1C4A	1C4E
Thickness:	4.44 x 10^{-5}cm	2.70 x 10^{-5}cm
Width:	0.0216 cm	0.0230 cm
Resistance (300°K):	6.9 ohms	20.0 ohms
Resistance (4.2°K):	0.25 ohms	1.1 ohms

T (°K)	I (ma)	I_c/w (amp/cm)	T (°K)	I (ma)	I_c/w (amp/cm)
3.347	30	1.46	3.357	9	0.39
3.328	35	1.70	3.339	12	0.52
3.314	40	1.94	3.322	16	0.70
3.281	52	2.52	3.295	19	0.83
3.247	65	3.15	3.281	22	0.96
3.198	83	4.03	3.267	25	1.09
3.141	97	4.70	3.229	33	1.44
3.091	114	5.28	3.189	40	1.74
3.014	135	6.25	3.118	59	2.56
2.926	164	7.60	3.074	70	3.04
2.859	183	8.48	3.053	75	3.26
2.824	193	8.94	2.999	87	3.78
			2.918	104	4.52
			2.833	120	5.21
			2.736	138	6.00
			2.581	162	7.05
			2.481	180	7.33
			2.324	210	9.14

C. Double width specimens.

Specimen no.:	6D2A	8D2A
Thickness:	1.39×10^{-5} cm	1.11×10^{-5} cm
Width:	0.0432 cm	0.0440 cm
Resistance (300°K):	10.2 ohms	15.6 ohms
Resistance (4.2°K):	0.55 ohms	0.75 ohms

T (°K)	I (ma)	I_c/w (amp/cm)	T (°K)	I_c (ma)	I_c/w (amp/cm)
3.396	15	0.35	3.407	10	0.23
3.381	22	0.51	3.394	16	0.36
3.368	30	0.70	3.378	25	0.57
3.355	38	0.88	3.352	38	0.86
3.341	45	1.04	3.322	55	1.25
3.298	64	1.48	3.287	67	1.52
3.255	82	1.90	3.244	92	2.09
3.195	108	2.50	3.198	111	2.52
3.118	138	3.20	3.141	137	3.12
3.039	183	4.24	3.094	175	3.98
2.984	204	4.72	3.050	204	4.63

Specimen no.:	5D3A	5D3C
Thickness:	2.22×10^{-5}cm	1.35×10^{-5}cm
Width:	0.0454 cm	0.0461 cm
Resistance (300°K):	8.0 ohms	16.3 ohms
Resistance (4.2°K):	0.13 ohms	0.5 ohms

T (°K)	I_c (ma)	I_c/w (amp/cm)	T (°K)	I_c (ma)	I_c/w (amp/cm)
3.371	32	0.71	3.394	15	0.33
3.357	37	0.82	3.381	20	0.44
3.344	46	1.01	3.368	28	0.61
3.314	58	1.27	3.341	37	0.80
3.287	74	1.63	3.314	50	1.08
3.238	103	2.27	3.267	73	1.58
3.176	132	2.91	3.226	93	2.02
3.128	157	3.46	3.176	117	2.54
3.077	180	3.96	3.128	152	3.30
3.021	211	4.65	3.094	181	3.98
			3.060	207	4.55

Specimen no.:	5D3D
Thickness:	1.35×10^{-5}cm
Width:	0.0535 cm
Resistance (300°K):	13.9 ohms
Resistance (4.2°K):	0.5 ohms

T (°K)	I_c (ma)	I_c/w (amp/cm)
3.386	30	0.56
3.368	37	0.69
3.341	56	1.05
3.312	75	1.40
3.281	95	1.77
3.250	118	2.20
3.220	136	2.54
3.180	160	2.99
3.151	182	3.40
3.128	192	3.59

Specimen no.:	7D4B	7D4C
Thickness:	2.70×10^{-5}	2.70×10^{-5}cm
Width:	0.0440 cm	0.0474 cm
Resistance (300^{o}K):	7.8 ohms	7.6 ohms
Resistance (4.2^{o}K):	0.5 ohms	0.5 ohms

T (^{o}K)	I (ma)	I_c/w (amp/cm)	T (^{o}K)	I_c (ma)	I_c/w (amp/cm)
3.389	18	0.35	3.389	9	0.19
3.376	18	0.35	3.373	19	0.40
3.363	18	0.35	3.357	31	0.65
3.349	18	0.35	3.341	38	0.80
3.331	35	0.68	3.295	58	1.22
3.314	35	0.68	3.258	75	1.58
3.287	44	0.86	3.214	94	2.09
3.258	50	0.97	3.164	115	2.43
3.214	76	1.47	3.111	134	2.82
3.164	100	1.94	3.057	163	3.44
3.111	129	2.50	3.010	187	3.95
3.060	161	3.11	2.984	205	4.32
3.007	200	3.88			

Specimen no.:	7D4D
Thickness:	2.70×10^{-5}cm
Width:	0.0536 cm
Resistance (300^{o}K):	5.9 ohms
Resistance (4.2^{o}K):	0.2 ohms

T (^{o}K)	I_c (ma)	I_c/w (amp/cm)
3.357	28	0.52
3.341	32	0.60
3.325	42	0.78
3.287	53	0.99
3.244	69	1.29
3.192	97	1.81
3.138	125	2.33
3.094	154	2.87
3.042	185	3.45
3.003	208	3.88

D. Confirmation runs.

Specimen: 12B2A

T (^oK)	I (ma)
3.391	7
3.378	12
3.360	17
3.344	25
3.295	39
3.235	55
3.151	74
3.060	90
2.962	110
2.810	135
2.671	159
2.481	190

10B3A

T (^oK)	I_c (ma)
3.381	10
3.368	15
3.355	17
3.314	23
3.273	31
3.202	46
3.141	63
3.081	78
2.999	94
2.906	110
2.797	130
2.671	155
2.501	185

11B4B

T (^oK)	I_c (ma)
3.378	9
3.360	14
3.341	20
3.295	35
3.258	50
3.192	70
3.108	99
3.032	135
2.926	188

Specimen: 3C2A

T (^oK)	I_c (ma)
3.394	8
3.381	10
3.368	17
3.312	39
3.167	80
3.063	101
2.981	119
2.897	142
2.810	165
2.717	185

2C3C

T (^oK)	I_c (ma)
3.399	9
3.386	13
3.363	19
3.258	53
3.111	113
3.067	132
2.918	200

Specimen: 8D2A		5D3C		7D4C	
T (^{o}K)	I_c (ma)	T (^{o}K)	I_c (ma)	T (^{o}K)	I_c (ma)
3.419	7	3.414	11	3.363	23
3.407	14	3.399	13	3.347	28
3.391	23	3.384	20	3.331	33
3.378	38	3.365	30	3.284	51
3.344	60	3.322	54	3.241	74
3.273	115	3.255	115	3.173	96
3.226	134	3.211	135	3.087	137
3.144	167	3.144	168	2.977	205
3.087	185	3.087	202		

E. Anomalous runs.

Specimen: 2C3D		5D3G (I)		5D3G (II)	
T (°K	I_c (ma)	T (°K)	I_c (ma)	T (°K)	I_c (ma)
3.391	8	3.407	8	3.419	8
3.378	10	3.394	13	3.407	10
3.368	14	3.368	22	3.394	15
3.303	22	3.341	34	3.368	22
3.241	32	3.301	45	3.341	42,45,55
3.176	38	3.255	52	3.301	56,59,64
3.101	42	3.205	58	3.241	66,70,80
3.003	28,37,46,60	3.160	68	3.195	66,79,84,95
2.922	33,40,48,69	3.108	75	3.141	71,88,93,104,138
2.824	32,42,50,77	3.057	75,86	3.067	89,97,105,119,136
2.722	40,58,90	2.999	85,90,110	3.003	89,97,111,124,131
		2.972	80,92,120	2.918	75,105,115,136,144
		2.881	80,100,133	2.833	85,111,126,138,160
		2.765	78,107,146		
		2.692	102,160		
		2.604	110,172		
		2.545	95,175		
		2.446	95,175		